Load-bearing capacities of ultra-thin occlusal veneers bonded to dentin

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Abstract: OBJECTIVES To test whether the load-bearing capacity of occlusal veneers made of ceramic or hybrid materials bonded to dentin does differ from those of porcelain-fused-to metal or lithium disilicate glass ceramic crowns. MATERIAL AND METHODS In 80 human molars, occlusal tooth substance was removed so that the defects extended into dentin, simulating defects caused by attrition/erosion. Restorations at a standardized thickness of either 0.5 mm or 1.0 mm were digitally designed. For both thicknesses, 4 test groups (n = 10 per group) were defined, each including a different restorative material: "0.5-ZIR": 0.5 mm thick zirconia (Vita YZ HT); "1.0-ZIR": 1.0 mm thick zirconia (Vita YZ HT); "0.5-LDC": 0.5 mm thick lithium disilicate ceramic (IPS e.max Press); "1.0-LDC": 1.0 mm thick lithium disilicate ceramic (IPS e.max Press); "0.5-HYC": 0.5 mm thick PICN (Vita Enamic); "1.0-HYC": 1.0 mm thick PICN (Vita Enamic); "0.5-COC": 0.5 mm thick tooth shaded resin composite (Lava Ultimate) and "1.0-COC": 1.0 mm thick tooth shaded resin composite (Lava Ultimate). Consecutively, the specimens were thermo-mechanically aged and then loaded until fracture. The load-bearing capacities (F) between the groups were statistically compared using the Kruskal-Wallis test ($p < 0.05$) and pairwise group comparison applying the Dunn's method. In addition, the results were compared to those of conventional lithium-disilicate ceramic crowns ("CLD") and to porcelain-fused to metal crowns ("PFM"). RESULTS The median F values for the 0.5 mm thin restorations were 1'350 N for 0.5-ZIR, 850 N for 0.5-LDC, 1'100 N for 0.5-HYC and 1'950 N for 0.5-COC. With CLD as the control, a significant difference was found between the groups 0.5-COC and 0.5-LDC (KW: $p = 0.0124$). With PFM as the control, the comparisons between PFM and 0.5-LDC as well as between 0.5-COC and 0.5-LDC were significant (KW: $p = 0.0026$). Median F values of 2'493 N in the group 0.5-ZIR, 1'165 in the group 0.5-LDC, 2'275 N in the group 0.5-HYC and 2'265 N in the group 0.5-COC were found. The medians of the F values for the 1.0 thick restorations amounted of 2'100 N in 1.0-ZIR, 1'750 N in 1.0-LDC, 2'000 N in 1.0-HYC and 2'300 N in 1.0-COC. Testing the multiple comparisons with Dunn's method no significant differences were found ($p > 0.05$). The median F values of the 1.0 mm thick restorations were: 2'489 N in the group 1.0-ZIR, 1'864 N in the group 1.0-LDC, 2'485 N in the group 1.0-HYC and 2'479 N in the group 1.0-COC. With CLD as the control group, a significant difference between zirconia and lithium-disilicate was found for the 0.5 ($p = 0.0017$) and 1.0 mm ($p = 0.0320$) thick specimens. Comparing the 0.5 mm thick specimens with CLD as the control, a significant difference was found between 0.5-HYC and 0.5-LDC ($p = 0.0017$). With PFM as the control, the comparison of lithium disilicate and zirconia was statistically significant for both thicknesses ($p = 0.0009$ for the 0.5 mm thick specimens; $p = 0.0074$ for the 1.0 mm thick specimens). In addition, with PFM as control group, significant differences were seen between 0.5-LDC and all other groups with restorations in 0.5 mm thickness ($p = 0.0017$). CONCLUSIONS Regarding their maximum load-bearing capacity, minimally invasive occlusal veneers made of ceramic, hybrid materials or polymeric materials can be applied to correct occlusal tooth wear with exposed dentin and thus replace conventional crown restorations in cases of normally expected intraoral bite forces.

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Load-bearing capacities of ultra-thin occlusal veneers bonded to dentin

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*: Equal contribution to the present investigation

Key words: ceramics, hybrid material, PICN, dental porcelain, resins, computer-aided design, computer-aided manufacturing, occlusal dental veneers, fatigue

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Abstract

Objectives: To test whether the load-bearing capacity of occlusal veneers made of ceramic or hybrid materials bonded to dentin does differ from those of porcelain-fused-to metal or lithium disilicate glass ceramic crowns.

Material and methods: In 80 human molars, occlusal tooth substance was removed so that the defects extended into dentin, simulating defects caused by attrition/erosion. Restorations at a standardized thickness of either 0.5 mm or 1.0 mm were digitally designed. For both thicknesses, 4 test groups (n = 10 per group) were defined, each including a different restorative material: "0.5-ZIR": 0.5 mm thick zirconia (Vita YZ HT); "1.0-ZIR": 1.0 mm thick zirconia (Vita YZ HT); "0.5-LDC": 0.5 mm thick lithium disilicate ceramic (IPS e.max Press); "1.0-LDC": 1.0 mm thick lithium disilicate ceramic (IPS e.max Press); "0.5-HYC": 0.5 mm thick PICN (Vita Enamic); "1.0-HYC": 1.0 mm thick PICN (Vita Enamic); "0.5-COC": 0.5 mm thick tooth shaded resin composite (Lava Ultimate) and "1.0-COC": 1.0 mm thick tooth shaded resin composite (Lava Ultimate). Consecutively, the specimens were thermo-mechanically aged and then loaded until fracture. The load-bearing capacities (F_{max}) between the groups were statistically compared using the Kruskal-Wallis test ($p < 0.05$) and pairwise group comparison applying the Dunn's method. In addition, the results were compared to those of conventional lithium-disilicate ceramic crowns ("CLD") and to porcelain-fused to metal crowns ("PFM").

Results: The median $F_{initial}$ values for the 0.5 mm thin restorations were 1'350 N for 0.5-ZIR, 850 N for 0.5-LDC, 1'100 N for 0.5-HYC and 1'950 N for 0.5-COC. With CLD as the control, a significant difference was found between the groups 0.5-COC and 0.5-LDC (KW: $p = 0.0124$). With PFM as the control, the comparisons between PFM and 0.5-LDC as well as between 0.5-COC and 0.5-LDC were significant (KW: $p = 0.0026$). Median F_{max} values of 2'493 N in the group 0.5-ZIR, 1'165 in the group 0.5-LDC, 2'275 N in the group 0.5-HYC and 2'265 N in the group 0.5-COC were found. The medians of the $F_{initial}$ values for the 1.0 thick restorations amounted of 2'100 N in 1.0-ZIR, 1'750 N in 1.0-LDC, 2'000 N in 1.0-HYC and 2'300 N in 1.0-COC. Testing the multiple comparisons with Dunn's method no significant differences were found ($p > 0.05$). The median F_{max} values of the 1.0 mm thick restorations were: 2'489 N in the group 1.0-ZIR, 1'864 N in the group 1.0-LDC, 2'485 N in the group 1.0-HYC and 2'479 N in the group 1.0-COC. With CLD as the control group, a significant difference between zirconia and lithium-disilicate was found for the 0.5 ($p = 0.0017$) and 1.0 mm ($p = 0.0320$) thick specimens. Comparing the 0.5 mm thick specimens with CLD as the control, a significant difference was found between 0.5-HYC and 0.5-LDC ($p = 0.0017$). With PFM as the control, the comparison of lithium disilicate and zirconia was statistically significant for both thicknesses ($p = 0.0009$ for the 0.5 mm thick specimens; $p = 0.0074$ for the 1.0 mm thick specimens). In addition, with PFM as control group, significant differences were seen between 0.5-LDC and all other groups with restorations in 0.5 mm thickness ($p = 0.0017$).

Conclusions: Regarding their maximum load-bearing capacity, minimally invasive occlusal veneers made of ceramic, hybrid materials or polymeric materials can be applied to correct occlusal tooth wear with exposed dentin and thus replace conventional crown restorations in cases of normally expected intraoral bite forces.

1. Introduction

The number of teeth decayed by caries has significantly decreased during the industrialization of western countries (Jordan et al., 2014; Steiner et al., 2010). In contrary, the loss of tooth substance due to erosion is a common finding in the population of developed countries (Schlueter and Luka, 2018). The reported prevalence in young patients is high and its progression with age can be expected (Bartlett et al., 2013; Jaeggi and Lussi, 2014). In order to compensate the loss of tooth substance caused by erosion, a prosthetic treatment may be indicated. Treatment concepts which propose the restoration of erosive tooth wear with full-crowns (Varma et al., 2018) require an additional and extensive preparation of the already hampered dentition (Edelhoff and Sorensen, 2002). Due to the potential biological complications of full-crown preparations such as vitality loss and need for endodontic treatment over time (Dahl, 1977; Pjetursson et al., 2007; Sailer et al., 2007; Valderhaug et al., 1997), these concepts nowadays may be replaced by less-invasive treatment strategies. For this purpose, the prosthetic rehabilitation applying a conservative preparation of the eroded teeth and using indirect minimally invasive approaches to restore them, have been suggested (Loomans et al., 2017).

As material for indirect minimally invasive treatment approaches glass ceramics are recommended (Muts et al., 2014). However, to use glass ceramic as a restorative material in the posterior area in reduced thicknesses may lead to a high rate of technical complications (Guess et al., 2013; Skouridou et al., 2013). Nowadays a vast amount of modified ceramic and hybrid-materials with altered mechanical properties have been introduced. These materials are claimed to overcome these technical problems and allow for restorations in reduced thicknesses. One strategy to optimize the mechanical performance of a restorative material, is to use a ceramic with a higher flexural strength and a higher fracture toughness in comparison to a conventional glass ceramic. Zirconia and lithium-disilicate are both restorative materials, which involve these properties (Christel et al., 1989; Elsaka and Elnaghy, 2016; Guazzato et al., 2004b; Miyazaki et al., 2013; Swain et al., 2016; Wagner and Chu, 1996). Another strategy to overcome the high rate of technical complications in thin restorations thicknesses is to combine the advantages known from ceramic and from polymer materials. For this reason, a hybrid material with a polymer-infiltrated ceramic network (PICN) was promoted (Awada and Nathanson, 2015; Swain et al., 2016). Furthermore, tooth-shaded resin composite materials for indirect reconstructions with a nanoparticle- and nanocluster-filled resin are available on the market (Awada and Nathanson, 2015).

Comparative studies, testing these reinforced ceramics, hybrid-materials and tooth shaded resin composite in thin restoration thicknesses are rare (Awada and Nathanson, 2015; Egbert et al., 2015; Ioannidis et al., 2018; Sieper et al., 2017). A previous study reported results of occlusal veneers bonded on enamel (Ioannidis et al., 2018). However, longevity of adhesion on to dentin as a consequence of aging could be anticipated to decrease over time (Breschi et al., 2008) which may decrease the survival of occlusal veneers. Therefore, the objective of this study was to test whether the load-bearing capacity of occlusal veneers made of these materials and bonded to dentin does differ from conventional preparations restored with porcelain-fused-to metal or lithium disilicate glass ceramic crowns. The hypothesis was that the load-bearing capacities would not be significantly different between the test- and the control-groups.

2. Material and Methods

2.1. Groups

The test groups (Table 1) consisted of occlusal veneers fabricated out of different restorative materials (zirconia, lithium disilicate, PICN, tooth shaded resin composite) in the two different thicknesses (0.5 and 1.0 mm) each. The subsequent groups were tested in 10 specimens per group: “0.5-ZIR”; “1.0-ZIR”; “0.5-LDC”; “1.0-LDC”; “0.5-HYC”; “1.0-HYC”; “0.5-COC”; “1.0-COC”. Two groups of 10 specimens each served as historical controls (Ioannidis et al., 2018) and contained of conventional crown preparations restored with CAD/CAM fabricated lithium-disilicate ceramic (“CLD”: IPS e.max CAD, Ivoclar Vivadent, Schaan, Liechtenstein) or porcelain-fused-to metal crowns (“PFM”: Creation by Willy Geller; Manufacturer Klema, Meiningen, Austria / Esteticor Special; Cendres Metaux, Biel, Switzerland).

2.2 Specimen preparation

Eighty extracted intact human molars were embedded in a self-curing resin (Dura Lay; Reliance Dental Manufacturing LLC, Worth, IL, USA) inside a hollow cylinder. For the test groups, the occlusal surface was prepared in order to mimic substance defects due to attrition/erosion (Figure 1). For this purpose, the occlusal enamel of the molars was removed and the preparation was extended into dentin. After removal of the occlusal cusps, the level of dentin was further removed approximately 1 mm in direction of the pulp. In addition, sharp edges were rounded off. After preparation, the exposed central dentin was still surrounded by a margin of enamel. During the entire study procedures, the specimens were stored in deionized water.

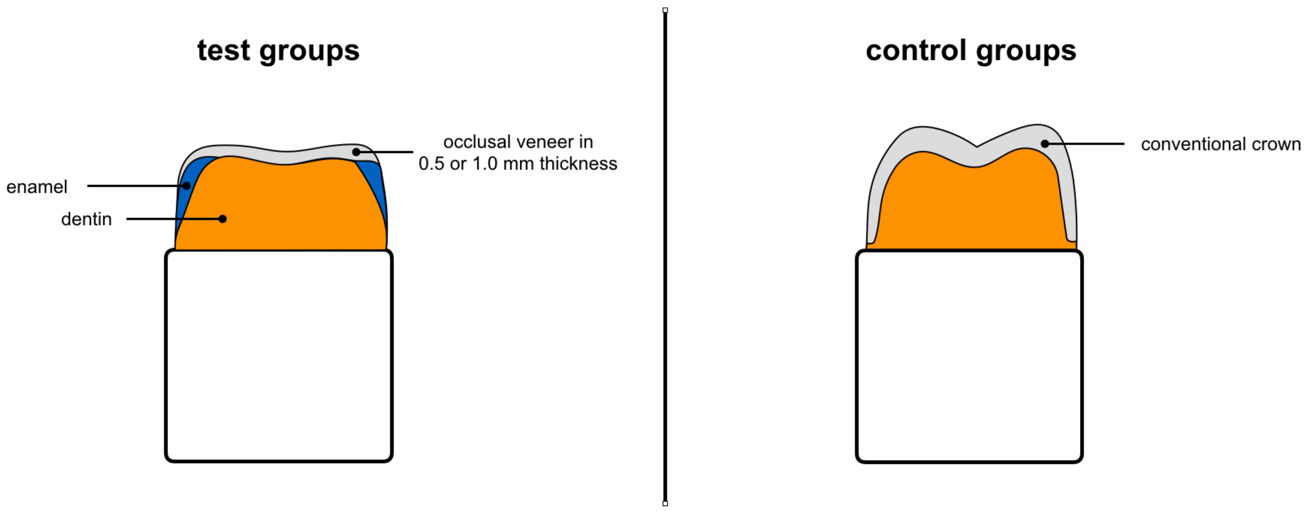
Table 1

Restorative materials used with their respective chemical composition.

Group	Restoration thickness	Restorative material	Composition
0.5-ZIR	0.5 mm	Yttria-stabilized tetragonal zirconia (Vita YZ HT; Vita Zahnfabrik, Bad Säckingen, Germany)	ZrO_2 (90.4 - 94.5 wt%), Y_2O_3 (4 - 6 wt%), HfO_2 (1.5 - 2.5 wt%), Al_2O_3 (0 - 0.3 wt%), Er_2O_3 (0 - 0.5 wt%), Fe_2O_3 (0 - 0.3 wt%)
1.0-ZIR	1.0 mm		
0.5-LDC,	0.5 mm	Lithium-disilicate ceramic (IPS e.max Press; Ivoclar Vivadent, Schaan, Liechtenstein)	SiO_2 (57 - 80 wt%), Li_2O (11 - 19 wt%), K_2O (0 - 13 wt%), P_2O_5 (0 - 11 wt%), ZrO_2 (0 - 8 wt%), ZnO (0 - 8 wt%), other oxides and ceramic pigments (0 - 10 wt%)
1.0-LDC	1.0 mm		
0.5-HYC	0.5 mm	PICN (Vita Enamic; Vita Zahnfabrik, Bad Säckingen, Germany)	Polymer part (14 wt%): UDMA; TEGDMA Ceramic part (86 wt%): SiO_2 (58 - 63%), Al_2O_3 (20 - 23%), Na_2O (9 - 11%), K_2O (4 - 6%), B_2O_3 (0.5 - 2%), ZrO_2 (< 1%), CaO (< 1%)
1.0-HYC	1.0 mm		
0.5-COC	0.5 mm	Tooth shaded resin composite (Lava Ultimate; 3M ESPE, Seefeld, Germany)	Matrix: bis-GMA, UDMA, bis-EMA, TEGDMA Filler: 80 wt%, silica (20 nm), zirconia (4-11 nm)
1.0-COC	1.0 mm		

Figure 1

Schematic drawings of the test and control groups. In the test groups, the preparation extended into dentin, surrounded by a border of enamel. The restorations in the test groups consisted of either 0.5 or 1.0 mm thick occlusal veneers in different restorative materials (zirconia, lithium disilicate, PICN, tooth shaded resin composite). For the control groups, conventional crowns were prepared and the teeth restored with different restorative materials (lithium disilicate, porcelain-fused to metal).



2.3 Scanning procedures, restoration design and fabrication

Digital impressions of the prepared teeth were made (Cerec Omnicam; Software-Version 4.4, Sirona, Bensheim, Germany) and transferred to a design software (InLab, Sirona). Depending on the group allocation, two different thicknesses were chosen for the design of the restorations being either 0.5 mm (range 0.3 - 0.7 mm) or 1.0 mm (range 0.8 - 1.2 mm). The method to standardize the restoration thickness was published recently elsewhere (Ioannidis et al., 2018).

The restorations for the groups 0.5-ZIR, 1.0-ZIR, 0.5-HYC, 1.0-HYC, 0.5-COC and 1.0-COC were directly milled out of the respective ingots using a 5-axis milling machine (MC X5; Sirona). For fabrication of the restorations in the groups 0.5-LDC and 1.0-LDC, first an acrylic template (Vita CAD Waxx; Vita Zahnfabrik) was milled out using the same milling machine. This template was consecutively used to produce pressed lithium-disilicate restorations (e.max Press; Ivoclar Vivadent) applying the “lost-wax and press-technique”.

2.4.1 Control groups CLD and PFM

The historical control groups (Ioannidis et al., 2018), which were tested in the same series, consisted of 10 specimens in each group. The embedded molars where prepared according to conventional crown preparation guidelines with circular butt joint margins of 0.8 - 1.0 mm width, a tapering angle of 10–12 degrees, an occlusal reduction of 1.3 – 1.8 mm and a minimal abutment height of 3.0 – 4.0 mm (Figure 1).

As described for the test groups, the prepared specimens were digitized (Cerec Omnicam, Sirona) and the restorations were digitally designed (InLab, Sirona). The dimensions of the designed crowns were as follows: occlusal thickness 1.5 mm, axial thickness 0.8 – 1.0 mm.

The crowns of the CLD group were milled out of pre-fabricated blocks (IPS e.max CAD; Ivoclar Vivadent) using a 4-axis milling machine (MCXL; Sirona). Consecutively, the restorations were sintered to full density (Programat CS 2; Ivoclar Vivadent) according to the manufacturer’s instructions.

For the PFM group, the designed crowns were milled out of a prefabricated ingot (Vita CAD Wax; Vita Zahnfabrik) using a 4-axis milling machine (MCXL; Sirona). These acryl polymer restorations served as templates to form the shape of the prospective restorations. The porcelain-fused-to-metal crowns were directly manufactured on the prepared teeth (Creation by Willy Geller; Manufacturer Klema, Meiningen, Austria / Esteticor Special; Cendres Metaux, Biel, Switzerland).

2.4 Cementation protocols

All restorations were cemented according the manufacturer's instructions for the respective materials used in the different groups (Table 2).

Table 2

Cementation protocols for the used test-materials.

Group	Applications steps on the tooth	Applications steps on the restoration	Cementation
0.5-ZIR, 1.0-ZIR	1. Apply 35% phosphoric acid (Ultraetch; Ultradent, Utah, USA) to the prepared enamel surfaces for 30 s. 2. Spray the surface with water for 30 s and consecutively gently air-dry. 3. Mix the two agents 1:1 (ED Primer A and B; Kuraray, Tokyo, Japan) for 3-5 s and apply the mixture for 60 s on the enamel, consecutively gently air-dry and light-cure for 30 seconds.	1. Air-abrade the inner surface of the tabletop (CoJet 50 µm 1.2 bar; 3M ESPE) for 15 s and consecutively gently air-dry. 2. Apply the agent (Clearfil Ceramic Primer; Kuraray, Tokyo, Japan) for 5 s, consecutively gently air-dry.	1. Mix the adhesive cement 1:1 (Panavia 21; Kuraray) für 20 s, apply on the restoration. 2. Apply and leave glycerin gel (Oxygard; Kuraray) on the edge of the restoration for 7 min before removing the gel with water-spray.
0.5-LDC, 1.0-LDC	1. Apply 35% phosphoric acid (Ultraetch; Ultradent, Utah, USA) to the prepared enamel surfaces for 30 s. 2. Spray the surface with water for 30 s and consecutively gently air-dry. 3. Apply the bonding agent (Heliobond; Ivoclar Vivadent) and consecutively gently air-dry (no light-cure).	1. Apply 5% hydrofluoric acid for 20 s (Ivoclar Vivadent). 2. Spray the surface with water for 60 s. 3. Apply the silane (Monobond Plus; Ivoclar Vivadent) for 60 s, before gently air-drying. 4. Apply the bonding agent (Heliobond; Ivoclar Vivadent) and consecutively gently air-dry (no light-cure).	1. Apply the adhesive cement, mix 1:1 (Variolink II; Ivoclar Vivadent) on the restoration. 2. Remove excess cement carefully before light-curing for 6 x 40 s.
0.5-HYC, 1.0-HYC	1. Apply 35% phosphoric acid (Ultraetch; Ultradent, Utah, USA) to the prepared enamel surfaces for 30 s. 2. Spray the surface with water for 30 s and consecutively gently air-dry. 3. Apply the bonding agent (Heliobond; Ivoclar Vivadent) and consecutively gently air-dry (no light-cure).	1. Apply 5% hydrofluoric acid for 60 s (Ivoclar Vivadent). 2. Spray the surface with water for 60 s. 3. Apply the silane (Monobond Plus; Ivoclar Vivadent) for 60 s, before gently air-drying. 4. Apply the bonding agent (Heliobond; Ivoclar Vivadent) and consecutively gently air-dry (no light-cure).	1. Apply the adhesive cement, mix 1:1 (Tetric Flow; Ivoclar Vivadent) on the restoration. 2. Remove excess cement carefully before light-curing for 6 x 40 s.
0.5-COC, 1.0-COC	1. Apply 35% phosphoric acid (Ultraetch; Ultradent, Utah, USA) to the prepared enamel surfaces for 30 s. 2. Spray the surface with water for 30 s and consecutively gently air-dry. 3. Apply the bonding agent (Scotchbond Universal Adhesive; 3M ESPE) on the tooth for 20 s, consecutively gently air-dry for 5 s (no light-cure).	1. Air-abrade the inner surface of the tabletop (CoJet 50 µm 1.2 bar; 3M ESPE) for 15 s and consecutively gently air-dry. 2. Apply the bonding agent (Scotchbond Universal Adhesive; 3M ESPE) on the inner surface of the table top for 20 s, consecutively gently air-dry for 5 s (no light-cure).	1. Apply the adhesive cement (RelyX Ultimate cement; 3M ESPE) on the restoration. 2. Remove excess cement carefully and light-cure for 3 x 30 s.

2.5 Aging procedures

The specimens were aged in a custom-made chewing simulator (Krejci et al., 1990) applying thermo-cycling (5 – 50° C, dwelling time 120 s) and chewing simulation (1’200’000 cycles, 49 N force and 1.67 Hz loading frequency). As antagonist with a vertical indenter movement of 1 mm, a corrosion-free steel indenter with a rounded polished tip (ø 8 mm) was used to load the specimens in axial direction to the occlusal plane. The integrity of the specimens after aging procedures was controlled under a stereomicroscope at a 1.25× magnification.

2.6 Static loading

The specimens were further investigated performing a static fracture load test using a universal testing machine (Zwick / Roell Z010; Zwick, Ulm, Germany). The indenter exposed force to the occlusal surface in a perpendicular direction with a crosshead speed of 1 mm/min until fracture of the specimen. The force needed to crack the specimen was recorded ($F_{initial}$) and the load, which was registered as soon as fracture load decreased by 20% of the maximum load (F_{max}).

On digital photographs and with loupes at a magnification of 2.5×, the failures were categorized into 4 scores: score 0 = no visible fracture, score 1 = cohesive fracture within the restoration, score 2 = cohesive fracture of the restoration and of the cement layer, score 3 = fracture of the restoration-cement-tooth complex.

2.7 Statistical analysis

The metric variables with mean, median, standard deviations, quartiles, minimum and maximum were described. Categorical variables were summarized by counts and proportions of the categories based on the material types and thickness. The comparisons of the group medians of the metric variables were performed with nonparametric methods (Kruskal-Wallis test). Multiple comparisons of two groups are based on adjusted p-values, using the method of Dunn (Bonferroni). The proportions of the categorical parameters with the chi-squares test were compared. P-values < 0.05 were considered to be statistically significant in all tests.

3. Results

It has to be stated that for the group 0.5-ZIR only 4 out 10 restorations could be fabricated and tested due to problems in reliably manufacturing the zirconia specimens.

3.1 Fatigue *resistance*

All tested specimens survived the thermo-mechanical aging procedures.

3.2 Load-bearing capacity

3.2.1 Restorations with 0.5 mm thickness

The median $F_{initial}$ values were 1’350 N for 0.5-ZIR, 850 N for 0.5-LDC, 1’100 N for 0.5-HYC and 1’950 N for 0.5-COC (Table 3, Figure 2). With CLD as the control, a significant difference was found between the groups 0.5-COC and 0.5-LDC (KW: $p = 0.0124$, 5 groups). With PFM as the control, the comparisons between PFM and 0.5-LDC as well as between 0.5-COC and 0.5-LDC were significant (KW: $p = 0.0026$, 5 groups).

The following median F_{max} values were found: 2’493 N for 0.5-ZIR, 1’165 N for 0.5-LDC, 2’275 N for 0.5-HYC and 2’265 N for 0.5-COC (Table 3, Figure 3). Using CLD as the control group, a significant difference between 0.5-ZIR and 0.5-LDC as well as between 0.5-HYC and 0.5-LDC was found (KW: $p = 0.0022$, 5 groups). Taking PFM as the control, the Kruskal-Wallis test ($p = 0.0009$, 5 groups) was significant between the group 0.5-LDC and the groups 0.5-COC, 0.5-HYC, 0.5-ZIR and PFM.

3.2.2 Restorations with 1.0 mm thickness

The median of the $F_{initial}$ values for the 1.0 thick restorations amounted of 2’100 N in 1.0-ZIR, 1’750 N in 1.0-LDC, 2’000 N in 1.0-HYC and 2’300 N in 1.0-COC (Table 3, Figure 2). The Kruskal-Wallis test detected significant differences with CLD (KW: $p = 0.0209$, 5 groups) or PFM (KW: $p = 0.0156$, 5 groups) as controls. However, the multiple comparisons with Dunn’s method did not show any significant differences ($p > 0.05$).

The respective medians for the F_{max} values for the 1.0 thick restorations were 2’489 N for 1.0-ZIR, 1’864 N for 1.0-LDC, 2’485 N for 1.0-HYC and 2’479 N for 1.0-COC (Table 3, Figure 3). With CLD as the control, the differences between the group 1.0-LDC and 1.0-ZIR were significant (KW: $p = 0.03205$ groups). With PFM as control the group, the Kruskall-Wallis test ($p = 0.0074$, 5 groups) found significant different medians. Applying the Dunn’s method, the difference between 1.0-LDC and 1.0-ZIR was significant ($p < 0.05$).

Table 3

The force required to crack the material ($F_{initial}$) and the load-bearing capacity (F_{max}) in Newton for all groups under investigation with mean, standard deviation (SD), first quartile (Q1), median, third quartile (Q3), minimum and maximum.

			F initial					F max				
	n	**group**	**Mean ± SD**	**Q1**	**Median**	**Q3**	**Range min to max**	**Mean ± SD**	**Q1**	**Median**	**Q3**	**Range min to max**
0.5 mm thick restorations	4	**0.5-ZIR**	1425 ± 359	1150	1350	1700	1100 to 1900	2382 ± 228	2265	2493	2499	2039 to 2502
	10	**0.5-LDC**	845 ± 320	500	850	1100	450 to 1300	1191 ± 382	846	1165	1581	578 to 1703
	10	**0.5-HYC**	1415 ± 569	1000	1100	2000	800 to 2400	1981 ± 617	1395	2275	2494	976 to 2499
	10	**0.5-COC**	1752 ± 695	1400	1950	2300	220 to 2400	2092 ± 439	1617	2265	2488	1439 to 2495
1.0 mm thick restorations	10	**1.0-ZIR**	2135 ± 245	1900	2100	2400	1800 to 2400	2483 ± 23	2485	2489	2491	2418 to 2497
	10	**1.0-LDC**	1690 ± 580	1200	1750	2100	600 to 2400	1851 ± 631	1291	1864	2485	767 to 2489
	10	**1.0-HYC**	1590 ± 542	1100	2000	2000	800 to 2000	2239 ± 493	2163	2485	2491	902 to 2495
	10	**1.0-COC**	2160 ± 306	2000	2300	2400	1600 to 2400	2328 ± 288	2170	2479	2490	1613 to 2494

Figure 2

Box-plots for the $F_{initial}$ values of the test groups 0.5-ZIR, 1.0-ZIR, 0.5-LDC, 1.0-LDC, 0.5-HYC, 1.0-HYC, 0.5-COC and 1.0-COC. The medians of the groups CLD and PFM were used as controls. Significant differences (KW $p < 0.05$) between the groups are marked with a dashed red bar.

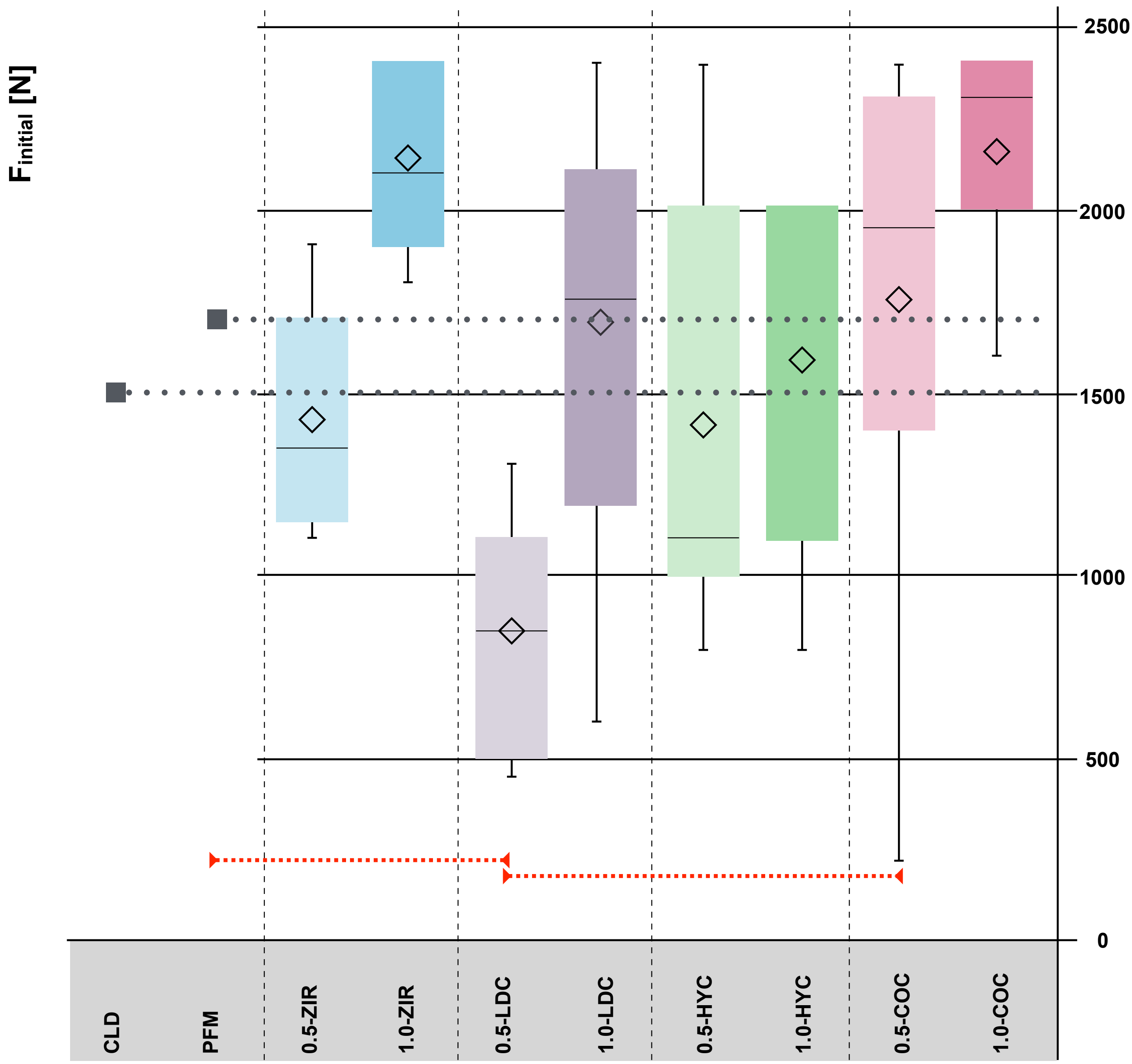
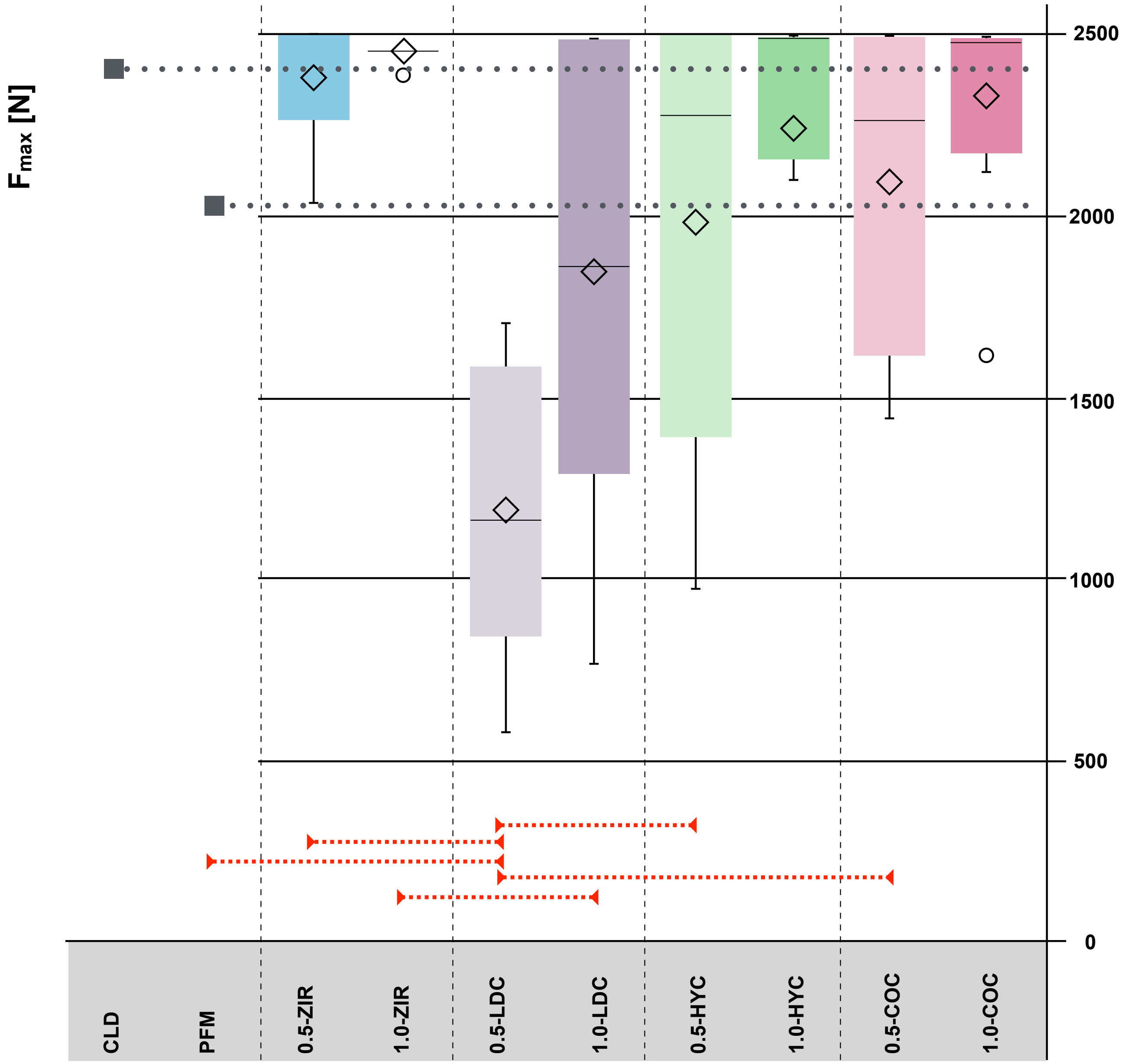


Figure 3

Box-plots for the F_{max} values of the test groups 0.5-ZIR, 1.0-ZIR, 0.5-LDC, 1.0-LDC, 0.5-HYC, 1.0-HYC, 0.5-COC and 1.0-COC. The medians of the groups CLD and PFM were used as controls. Significant differences (KW $p < 0.05$) between the groups are marked with a dashed red bar.



3.3 Failure types

The Chi-squares tests comparing the failure types of the control and test groups (Table 4) showed no statistically significant differences, neither for the 0.5 mm thin specimens ($p = 0.7779$) nor for the 1.0 mm thick specimens ($p = 0.1476$).

Table 4

Failure types with percentage of no visible fracture (score 0), cohesive fracture within the restoration (score 1), cohesive fracture of the restoration and of the cement layer (score 2) and fracture of the restoration-cement-tooth complex (score 3).

Group	Score 0 [%]	Score 1 [%]	Score 2 [%]	Score 3 [%]
0.5-ZIR	0	0	100	0
0.5-LDC	0	0	100	0
0.5-HYC	10	10	70	10
0.5-COC	0	10	90	0
1.0-ZIR	20	0	80	0
1.0-LDC	0	20	70	10
1.0-HYC	0	40	50	10
1.0-COC	20	0	70	0

4. Discussion

In the present investigation, no complications or failures in any of the tested materials occurred during the aging phase, meaning that all materials withstood the thermo-mechanical aging which simulates dynamic loading forces under clinical conditions. The load-bearing capacities of the 1.0 mm thick minimally invasive occlusal veneers in the different tested materials were found to be not different to the ones of the control materials representing conventional treatment concepts. Using the test materials in a thickness of 0.5 mm this applies for all materials expect for lithium disilicate. The outcomes for lithium disilicate were significantly inferior when compared to the other tested groups.

During mastication, teeth and restored teeth must resist cyclic loads and temperature changes in the wet oral cavity. In order to simulate physiological conditions, the dynamic fatigue and the temperature alterations were simulated with a chewing simulator under wet conditions. In total 1'200'000 cycles of dynamic loading were applied, which is reported in literature to simulate 5 years of clinical service (Bates et al., 1975; DeLong and Douglas, 1991; Steiner et al., 2009). To mimic conditions during normal chewing function and swallowing, a load of 49 N was applied at 1.67 Hz loading frequency. The applied aging procedure did not lead to any failure of the tested restorations. Thus, this implies that the tested minimally invasive occlusal veneers bonded to dentin and made out of zirconia, lithium-disilicate, PICN or tooth shaded resin material can withstand normal clinical conditions irrespective of the restoration thickness. Normal masticatory forces however, can reach higher values than 49 N. In the posterior region they can range from 200 to 540 N and even raise up to 800 N in patients with bruxism (Bates et al., 1976). Taking this into consideration, one has to pay attention on the values which are achieved by static loading tests. The median $F_{initial}$ values for the 0.5 mm thick specimens were at least 850 N, which is supposed to be higher than extreme masticatory loading forces. By increasing the restoration thickness to 1.0 mm, the median $F_{initial}$ values were at least 1'750 N, which is by far higher than expected under extreme clinical conditions. Looking at the minimum values of the forces which were required to crack the specimens, some materials showed values beneath these 800 N. Occlusal veneers made out of lithium disilicate formed cracks starting at 450 N in a thickness of 0.5 mm and at 600 N in a thickness of 1.0 mm. Testing the specimens which used the tooth shaded resin material as restorative material for the occlusal veneers, the crack formation started at 220 N for the 0.5 mm thick specimens. This may indicate that these two materials are not ideal to restore patients in which high loading forces can be expected and an alternative material selection should be considered. In contrary, for zirconia the minimal forces which are required to form cracks within the material were 1’100 N. For PICN, the minimal forces were 800 N, which is in accordance to another study revealing failures in PICN-crowns only at very high loads (El Zhawi et al., 2016). Thus, it is assumed that these materials are supposed to withstand high masticatory forces.

When comparing the $F_{initial}$ and F_{max} values of the minimally invasive treatment concepts to the conventional treatment concepts, differences were found only between the test material lithium disilicate in a thickness of 0.5 mm and the control group with the porcelain-fused to metal crowns. These results contradict recently published data, where no differences were found between the 0.5 mm thick lithium disilicate occlusal veneers and the same control (Ioannidis et al., 2018). Whereas in the present investigation the occlusal veneers were bonded to dentin, in the mentioned study occlusal veneers of 0.5 mm thickness were bonded to enamel. In tendency, lithium-disilicate restorations bonded to enamel show higher fracture resistances than those having dentin as substrate (Clausen et al., 2010). This was found in a study evaluating the influence on the masticatory fatigue and the fracture resistance of restorations bonded either to enamel or to dentin (Clausen et al., 2010). Similar to the present study, all specimens survived the aging procedures irrespective of the bonding substrate (Clausen et al., 2010). The median fracture resistances of the restorations bonded to dentin however, amounted 3’840 N, whereas the specimens having enamel as a bonding substrate reached values of 4’173 N (Clausen et al., 2010). In contrast to the 0.5 mm thick lithium disilicate restorations, the 1 mm thick occlusal veneers showed no differences compared to the control groups. A study tested the influence of the thickness of lithium disilicate occlusal veneers on the median fracture resistance (Sasse et al., 2015). It was shown that the ceramic thickness has an influence on the mean fracture resistance (Sasse et al., 2015). The respective values were 2’370 N for a thickness of 0.3 – 0.6 mm and 3’000 N for occlusal veneers in a thickness of 0.7 – 1.0 mm (Sasse et al., 2015). The authors suggested that a minimum thickness of 0.7 – 1.0 mm is necessary to restore teeth with pressed lithium disilicate occlusal veneers (Sasse et al., 2015).

The significantly lower $F_{initial}$ and F_{max} values of the lithium disilicate reconstructions in comparison to the values obtained in the group with the porcelain-fused to metal crowns are unexpected for an additional reason. Normally, monolithic reconstructions achieve higher values than manually veneered crowns as they come along with more favorable mechanical properties (Guazzato et al., 2004a). This is due to the high rate of edge chipping in manually layered ceramic structures which as a consequence should result in low $F_{initial}$ values (Ozcan and Niedermeier, 2002; Raigrodski et al., 2012). In this regard, monolithic reconstructions as in the case of zirconia and lithium disilicate usually deliver more favorable outcomes which could be confirmed for monolithic zirconia in this study.

The inherent mechanical properties of the materials tested in this study, did not necessarily correlate to the final load-bearing capacity. Normally, the tested materials show evident variations in terms of fracture strength and fracture toughness. In this context, the highest values usually are measured when zirconia as a restorative material is tested (Denry and Kelly, 2008; Guazzato et al., 2004b). These values are followed by the ones obtained by lithium disilicate, hybrid materials and polymeric materials (Della Bona et al., 2014; Guazzato et al., 2004a; Porto et al., 2018). The missing correlation between the normally achieved fracture strength and fracture toughness values and the load-bearing capacities found in this study, could be attributed to the adhesion properties of the luting cement bonded to the dentinal substrate and the occlusal veneer material. In the present investigation not the mechanical property of the restorative material itself, but the entire tooth-cement-restoration complex was tested. As crack formation usually starts from the zone of cementation, a proper adhesion of the restoration to the tooth is crucial and dictates the longevity of adhesion and thus the load-bearing capacity (Zhang et al., 2009). In this context it has to be mentioned that polymeric materials are known to come along with superior adhesion properties when compared with ceramic materials (Ozcan et al., 2005). The adhesion between the restorative material and the tooth could compensate the individual inferior mechanical properties of some of the tested materials (Ozcan et al., 2005; Ozcan et al., 2007). The reason for the higher median F_{max} values obtained for polymeric or hybrid materials when compared to lithium disilicate, could be explained on these grounds. Contrary to the previous report (Breschi et al., 2008), adhesion to dentin was not a limiting factor for the longevity of occlusal veneers tested in this study.

Load-to-fracture tests has been previously criticized (Kelly et al., 2012). In this context, the type of test employed in this study has certain limitations. Thus, contact stresses measurements at the wear facets and finite element analyses and damage mechanics should be further investigated in future studies. One other aspect which requires further studies is the variation of the luting cement type. In this study, based on the best available knowledge, conditioning methods and the cement type were selected in conjunction with the corresponding material tested. From adhesion perspective to the reconstruction material, this approach could be considered appropriate. However, some of the selected cements may present less favorable adhesion on the dentin which could be further investigated (Ozcan and Mese, 2012).

5. Conclusions

Regarding their load-bearing capacity minimally invasive occlusal veneers made of zirconia, lithium-disilicate, PICN or tooth shaded resin composite can be recommended to restore worn teeth with exposed dentin and thus replace conventional treatment concepts with full crown restorations. Minimum load-bearing capacities all exceed the normally expected intraoral bite forces. Clinicians should note that occlusal veneers in a thickness of 0.5 mm and made out of zirconia are difficult to fabricate which may limit their clinical indication for ultra-thin reconstructions.

Conflict of Interest

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